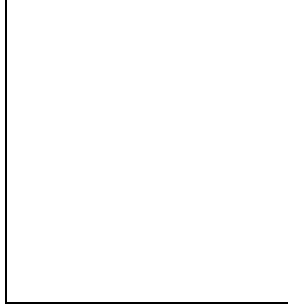


COBRAS/SAMBA AND MEASUREMENTS OF THE SUNYAEV-ZELDOVICH EFFECT

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Abstract

The recently approved COBRAS/SAMBA cosmic microwave background (CMB) mission will also have a major impact on measurements of the Sunyaev-Zeldovich (SZ) effect. The frequency of three of the channels (150 GHz, 217 GHz, 353 GHz) are chosen to optimize measurements of the thermal and kinetic SZ effect mainly caused by hot gas in clusters of galaxies. Estimates of the number of detected clusters are somewhat uncertain due to incomplete knowledge of the gas mass function of clusters and the distribution of hot gas at large radii. Straightforward interpolation of X-ray observations of the 200 X-ray brightest clusters gives a firm lower limit of ~ 3000 detected clusters of which roughly half should be resolved. If the gas distribution of clusters should turn out to be favourable and/or the cluster evolution with redshift is weak, this number could be higher by a factor of up to ten. Using an optimal filtering technique a measurement of the bulk peculiar velocity of a sample of about 200 of the resolved clusters will be possible with a 1σ error of $100 - 200 \text{ km s}^{-1}$.

1 Sensitivity of COBRAS/SAMBA

For an unresolved cluster the “SZ-flux” due to Compton scattering by hot electrons can be written as

$$S_\nu = f_\nu g(h\nu/kT) Y, \quad (1)$$

where $g(h\nu/kT)$ describes the frequency dependence of the Compton distortion (Fig. 1), f_ν is a normalization constant and $Y = \int y d\Omega$ is the Compton y parameter integrated over solid angle [1] [2] [3]. Y is proportional to the typical mass times the mass-weighted temperature within the radius where the density profile of the cluster becomes steeper than isothermal

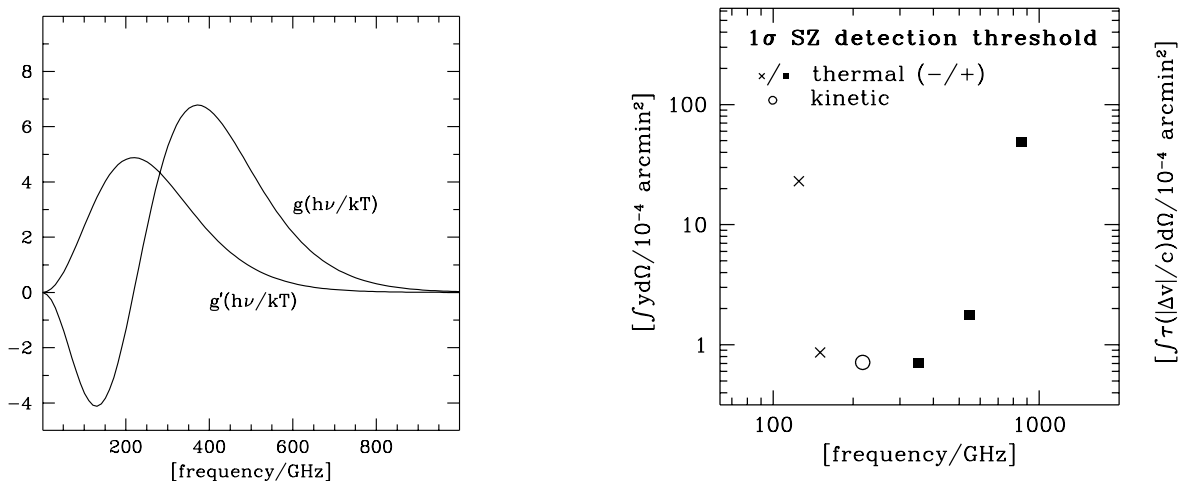


Figure 1: The left panel shows the frequency dependence of the thermal (g) and kinetic SZ (g') effect (equation 1 and 2). In the right panel the 1σ SZ detection threshold of the high frequency channels is shown in terms of the integrated Compton parameter $Y = \int y d\Omega$.

(and/or the gas temperature starts to drop). The crosses and squares in Figure 1b show the 1σ SZ detection threshold of the high frequency channels in terms of Y . A typical value for the “SZ-channels” at 150 and 353 GHz (maximum negative/positive SZ-flux) is 10^{-4}arcmin^2 . This takes only detector noise into account and will be somewhat increased by residual noise from the foreground subtraction procedure. $3 - 10 \times 10^{-4}\text{arcmin}^2$ should be considered as a reasonable range for the expected detection threshold of an unresolved cluster (marked by the shaded region in Figure 2.)

2 SZ number counts of unresolved clusters

Straightforward interpolation of the properties of a flux-limited sample of the 200 X-ray brightest clusters [4] by a factor 3-5 in flux gives a firm lower limit of ~ 3000 detected clusters. More accurate estimates are difficult because the typical gas mass and mass-weighted temperature within the radius where the density profile of the cluster becomes steeper than isothermal (and/or the gas temperature starts to drop) are difficult to determine from X-ray observations which generally probe the gas and temperature distribution at considerably smaller radii. The typical Y -parameter of clusters of a given present-day number density is probably uncertain by a factor of two. The estimated number counts are also sensitive to

- the exact shape of the present-day mass function, especially the slope at large masses,
- the details of the assumed evolution of the cluster mass/temperature function,
- and the cosmological parameter.

Nevertheless, the Press-Schechter formalism can be used to evolve the observed present-day mass function of clusters backward in time to get a feeling for the influence of the uncertain

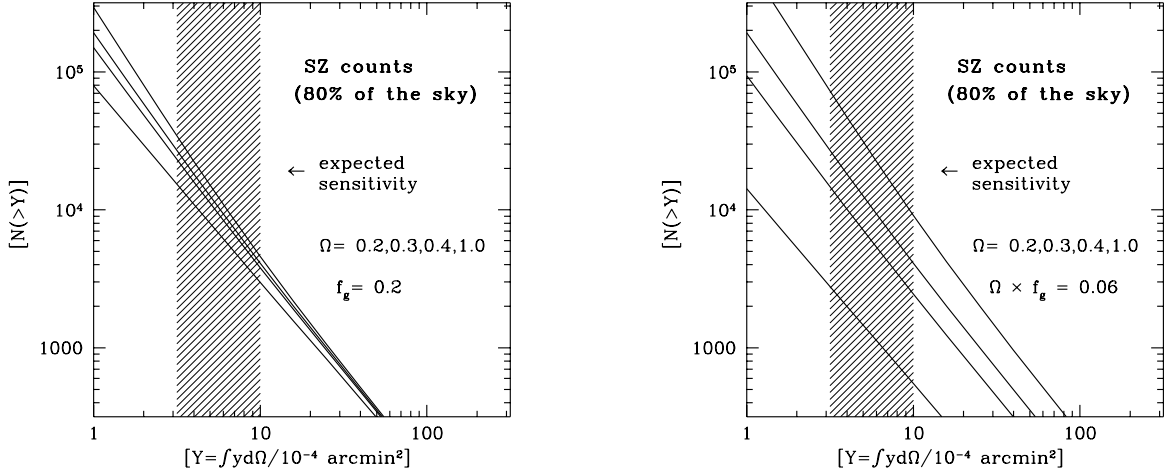


Figure 2: The expected number of detected clusters is plotted as function of the integrated Compton parameter $Y = \int y d\Omega$ for different values of the total matter density Ω as indicated (Ω decreasing upwards). The present-day mass function of clusters was evolved backwards in time using the Press-Schechter formalism. An spectral index of $n = -1$ for the primordial density fluctuation spectrum on cluster scales is assumed. The expected sensitivity of COBRAS/SAMBA is indicated by the shaded area. The left panel is for fixed gas mass fraction $f_g = 0.2$, while the right panel assumes compatibility with the nucleosynthesis constraint $\Omega \times f_g = 0.06$.

parameter [5] [6]. Assuming the usual observationally normalized scaling of the cluster temperature $T \propto M^{2/3} (1+z)$ we can work out the expected number counts $N(>Y)$. In Figure 2 these are shown for different values of Ω and different assumptions for the total fraction of hot gas. The left panel assumes a fixed gas mass fraction while the right panel assumes a gas mass fraction compatible with the nucleosynthesis constraint. The total number of clusters detected by COBRAS/SAMBA will depend strongly on the assumed sensitivity ($N \sim Y^{-3/2}$). The large difference between the two panels illustrates the uncertainties due to our insufficient knowledge of the total mass of hot gas in clusters.

3 Properties of the detected cluster sample

The properties of the detected cluster sample will also depend on the uncertainties mentioned above. If a detection threshold of $3 \times 10^{-4} \text{ arcmin}^2$ and $\Omega = 1$ is assumed a sample of 10^4 clusters is expected. This is about a factor of two larger than the number of clusters in the extended Abell catalogue. As shown in Figure 3a the typical redshift would be $z = 0.1$, very similar to that in the Abell catalogue, while the typical mass would be somewhat smaller. Unfortunately, the sensitivity and spatial resolution of COBRAS/SAMBA will not be sufficient to make use of the fact that the “surface brightness” of the SZ effect is independent of redshift. Figure 3b shows that a flat redshift distribution would only be seen with considerably better sensitivity and in a low Ω universe. However, a high redshift tail might still be seen if Ω is low [7].

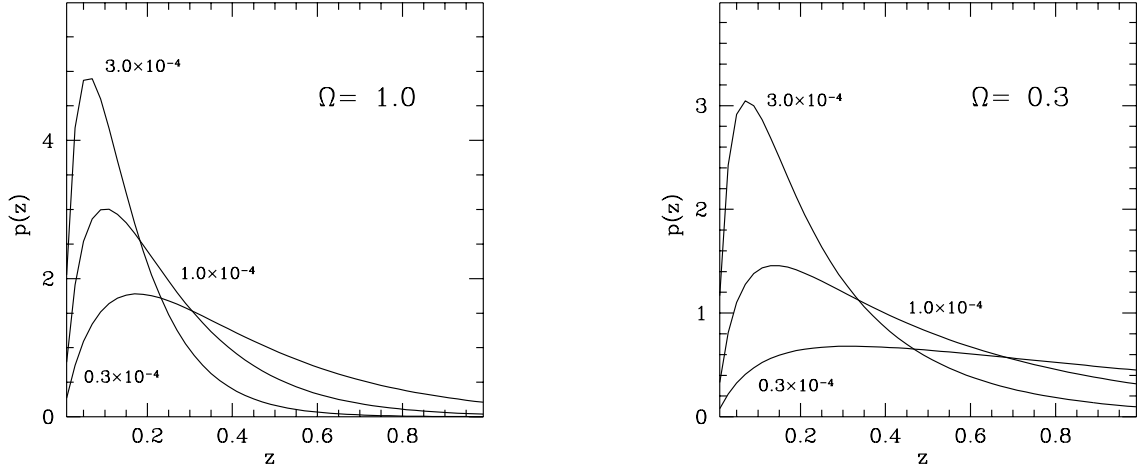


Figure 3: The left panel shows the expected redshift distribution for $\Omega = 1$ and for different sensitivity limits in terms of the integrated Compton parameter $Y = \int y \, d\Omega$ as indicated on the plot. The right panel is the same for $\Omega = 0.3$.

4 The kinetic SZ effect

For an unresolved cluster the kinetic “SZ-flux” due to peculiar motion of the hot gas in a cluster with respect to the CMB can be written as

$$S_\nu = f'_\nu g'(h\nu/kT) \int \tau |v_{\text{pec}}/c| \, d\Omega, \quad (2)$$

where $g'(h\nu/kT)$ describes the frequency dependence of the kinetic distortion (Fig. 1a), f'_ν is a normalization constant, τ is the Thompson optical depth and v_{pec} is the peculiar velocity of the cluster. The frequency dependence is that of a temperature fluctuation in the CMB and for a typical cluster the change in brightness temperature at the cluster center is of order

$$\Delta T \sim 30 \left(\frac{n_e}{3 \times 10^{-3} \text{ cm}^{-3}} \right) \left(\frac{r_c}{0.4 \text{ Mpc}} \right) \left(\frac{v_{\text{pec}}}{500 \text{ km s}^{-1}} \right) \mu\text{K}, \quad (3)$$

where n_e is the electron density in the core, r_c is the core radius and we have scaled to the values of the Coma cluster (assuming a distance of 140 Mpc) [8] [2]. The open circle in Figure 1b shows the sensitivity of COBRAS/SAMBA for an unresolved cluster in terms of $\int \tau |v/c| \, d\Omega$.

5 Measuring bulk velocities of clusters

For the kinetic effect the expected noise level due to confusion with primary fluctuations is generally of order or larger than the expected signal. It is therefore essential to use the knowledge of the CMB “noise” properties and the gas distributions of the individual clusters (which can be obtained by the mission itself and from X-ray observations, respectively). This knowledge makes it possible to analyze the CMB maps of resolved clusters with a spatial filter optimized for individual clusters. An improvement in signal-to-noise by a factor of two is easily achievable, and even a factor of 10 is possible if the gas mass distribution is well known from a high-quality X-ray map [9]. The final signal-to-noise ratio depends crucially on the cosmological model and

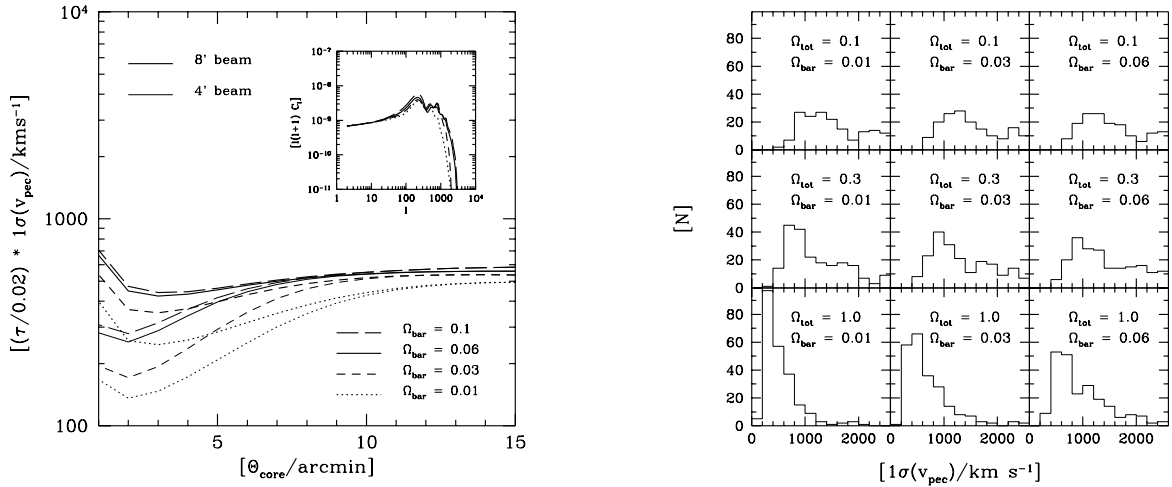


Figure 4: The left panel shows the 1σ error in the determination of the peculiar velocity as a function of the core radius of the cluster using an axisymmetric “optimal” filter function for a standard CDM scenario ($\Omega_{tot} = 1$, $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$) with varying baryonic fraction. The pixel noise is fixed and corresponds to $7 \mu\text{K}$ in the $4'$ (FWHM) beam. Thick curves are for a beam size of $8'$ and thin curves are for a beam size of $4'$. The inset shows the angular power spectra of temperature fluctuations for the three cosmological models. The right panel shows the distribution of expected 1σ errors of peculiar velocity measurements for the XBACs cluster sample for different cosmological models. Ω_{tot} and Ω_{bar} vary as indicated in the plot. An axisymmetric optimal filter was applied using a β -model for the cluster gas distribution.

the angular resolution of the instrument (Fig. 4a), and it is not currently clear whether a meaningful peculiar velocity measurement for individual clusters will be possible. Prime candidates are X-ray luminous clusters at intermediate redshift with core radii just below the Doppler peak scale. For a favourable but still rather standard cosmological scenario (standard CDM with low baryon fraction) and a good angular resolution ($4'$ FWHM), the peculiar velocity of as many as 30 individual clusters might be determined accurately. Even if this is impractical, it should still be possible to determine the bulk motion of an ensemble of 200 X-ray luminous clusters at redshifts $\gtrsim 10000 \text{ km s}^{-1}$ with an accuracy of order $100 - 200 \text{ km s}^{-1}$ (Fig. 4b).

6 Concluding remarks

COBRAS/SAMBA will produce the first all-sky SZ maps. In these maps most known clusters of galaxies will be detected roughly half of which will be resolved. It will therefore be possible to study the gas distribution of a large sample of clusters out to the virial radius. Once the cosmological parameter are known with good precision (the primary aim of the COBRAS/SAMBA mission) problems like a possible clumping of the gas can be addressed. Relativistic corrections to equation (1) and (2) might also allow to achieve accurate measurements of the temperature of the cluster gas [3] [10]. Comparison of SZ and X-ray properties of clusters will significantly advance our understanding of cluster evolution. If the gas mass fraction in clusters is high and there is as little evolution in the cluster population as indicated by current X-ray observation the SZ effect might also be a suitable tool to detect clusters at high redshift in appreciable numbers. So far, not much is known about bulk velocities on scales larger than 5000 to 10000 km s^{-1} . The measurement of the bulk velocity of a volume-limited sample of 119 Abell clusters out to a

distance of 15000 km s^{-1} gave a value considerably higher than expected in most cosmological scenarios [11]. The completely independent measurement by COBRAS/SAMBA on even larger scales should clarify this situation.

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